Mirror Technology Days

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TRS Technologies

High Frequency Phased Arrays for SiC NDE

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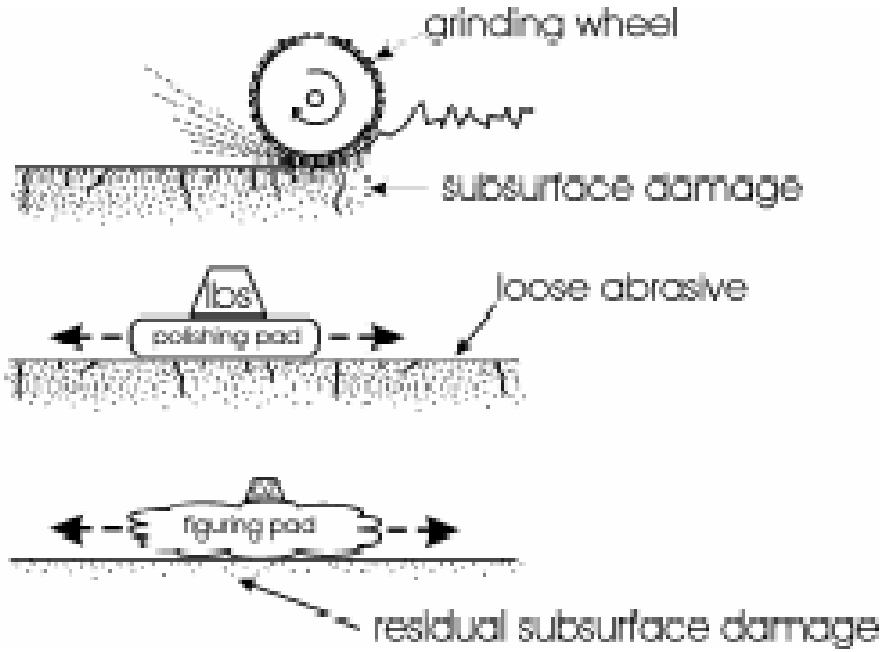
- Authors would like to acknowledge the helpful discussions from Dr. Larry Matson at AFRL.

Outline

- **Background**
  - -- Ultrasound NDE
  - -- PCMUT (Piezo-Composite Micromachined Ultrasound Transducer)
- **High Frequency Phased Array**
  - -- Array specifications
  - -- Modeling results
  - -- Phased array prototyping
- **Summary**

NDE for Ceramics

Ceramic Defects: crack, void, delamination, residue stress, inclusion, etc.

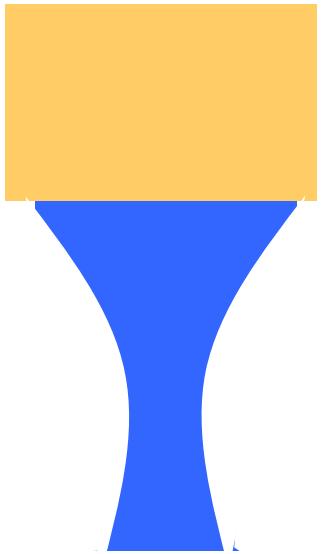


-- RAPT Industries, "Rapid Fabrication of Lightweight SiC Mirrors Using RAPTM Processing", Mirror Tech Days'06, Albuquerque, AL, 2006.

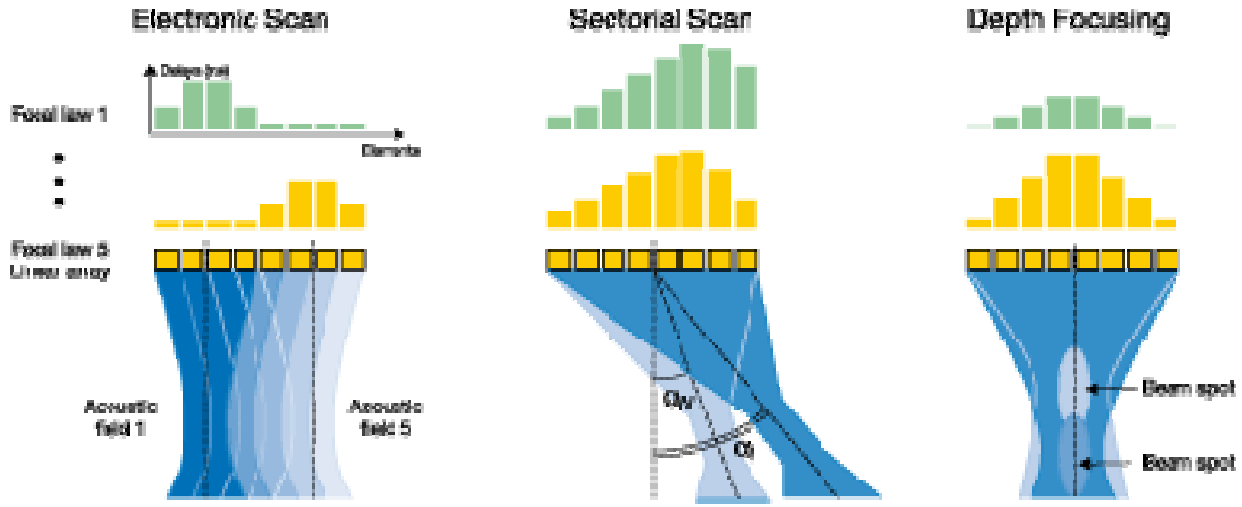
- Optical metrology: can only detect surface damage.
- X-ray: can not distinguish damage at various depths and has limited resolution.
- Acoustic NDE: can detect both surface and sub-surface damage. Need high frequency phased array for in-situ real time imaging with high spatial resolution.

Ultrasound NDE

Single Element



Phased Array



- Frequency, F#: high resolution at both axial and lateral, limited penetration depth
- Mechanical scanning

- Frequency, element numbers: high resolution in axial, lateral and sectoral direction, high penetration depth;
- Electronic scanning

--*M. Moles, "Ultrasonic Phased Array", http://www.olympusndt.com/en/ultrasonic-phased-array/.*

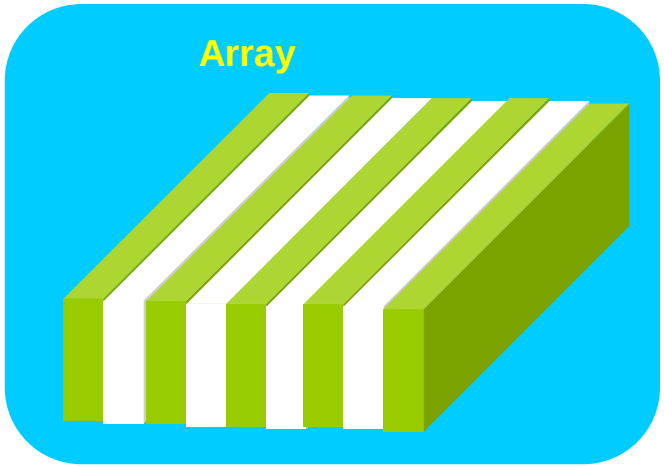
High Frequency Ultrasound

➢**Currently available HF transducers**

-- Piezoelectric Materials: ZnO, $LiNbO_3$, PVDF, and PZT—low piezoelectric response

-- Thickness mode: $k_t < 0.5$

-- Array: frequency < 20 MHz, limited in fabrication of fine pitches (~$\lambda/2$)

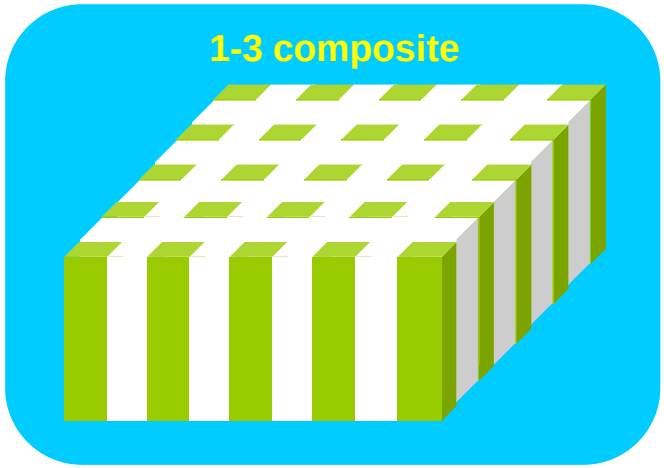


➢**TRS Approach: PC-MUT**

-- Material: single crystal piezoelectric 1-3 composite—high piezoelectric response

-- Effective “33” mode: $k_{33} > 0.7$ (@ 40 MHz)

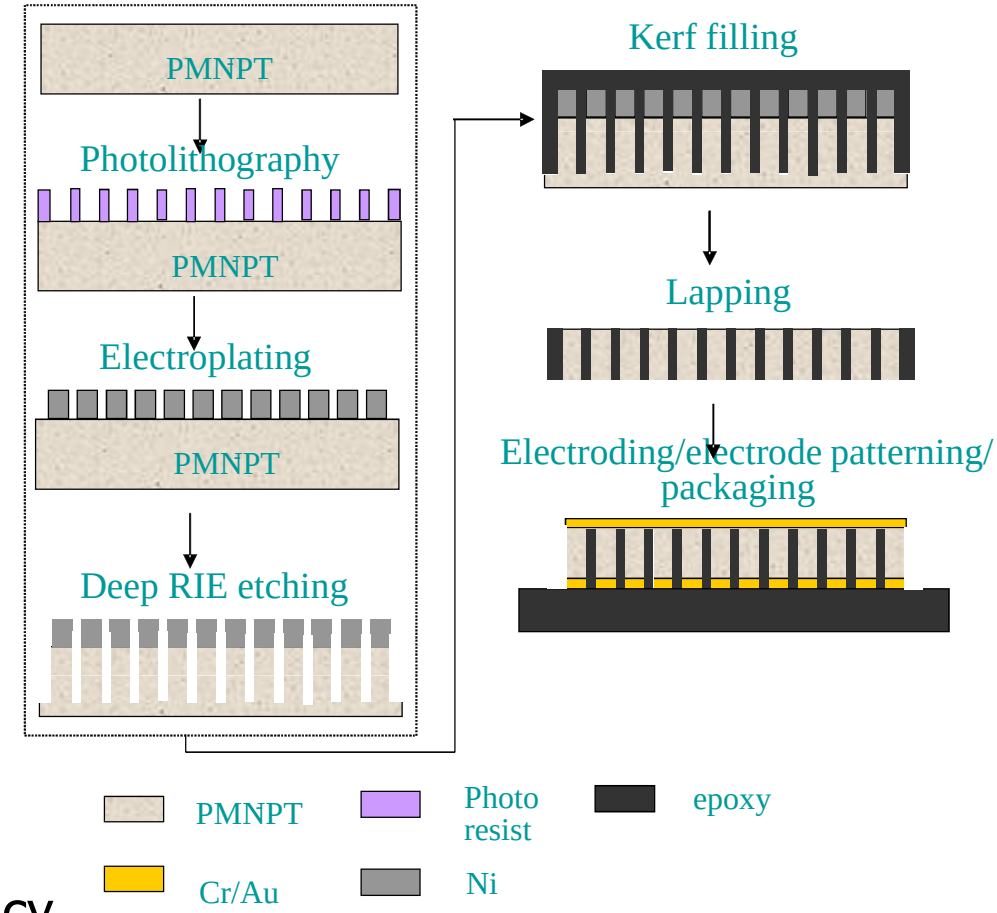
-- Array: fine pitches can be fabricated using photolithography based deep reactive ion etching process



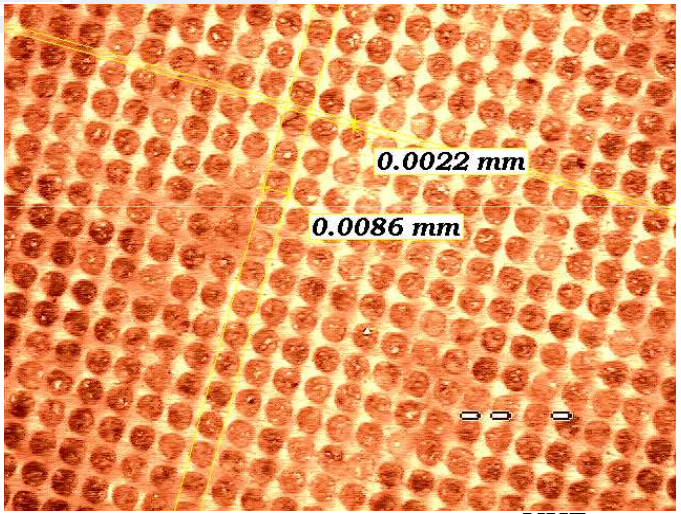
High Frequency Composite Fabrication

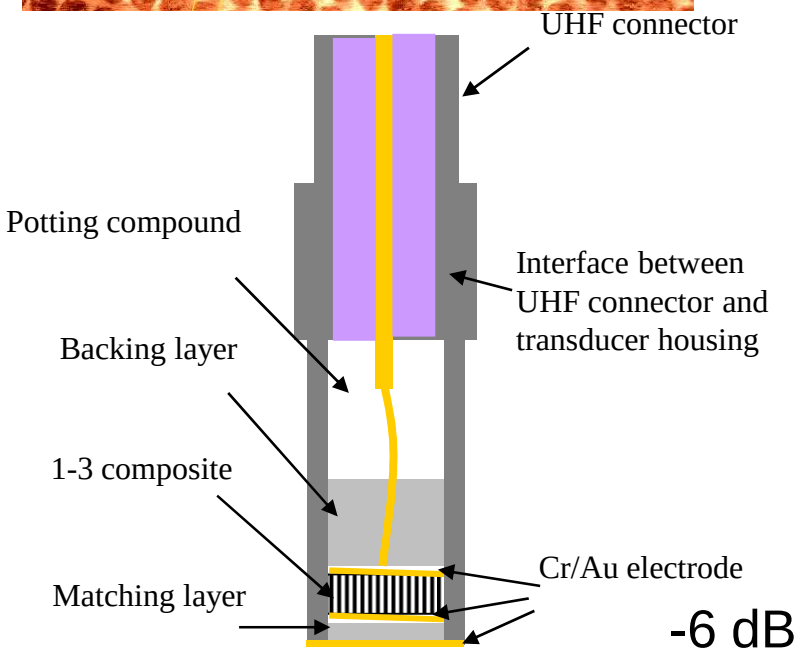
PC-MUT

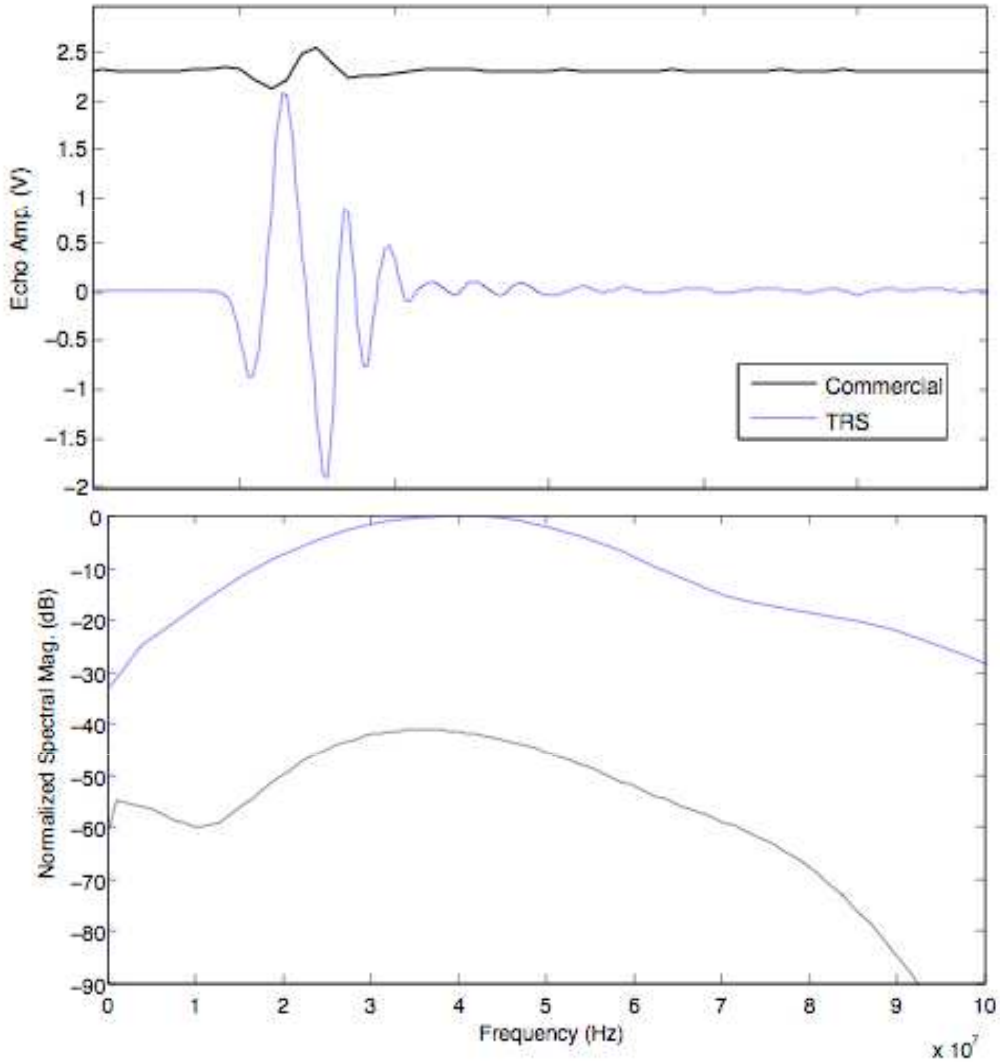
- Use Photolithography & Plasma Etching
- Form Fine Features in High Performance Single Crystal
- High Frequency, High Performance Composite
- Very High Resolution, Broad Bandwidth Single Elements
- Basis for Very High Frequency Integrated Array Transducers



Pulse-Echo Tests (75 MHz)



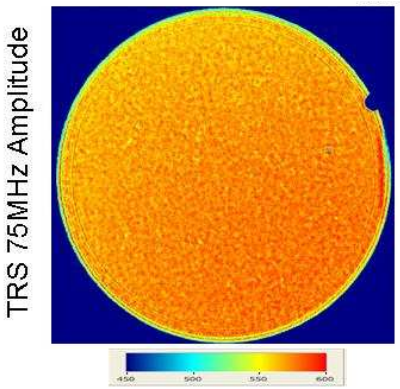


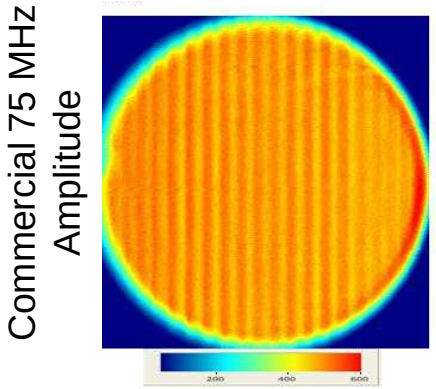


-6 dB bandwidth: ~ 80-90%

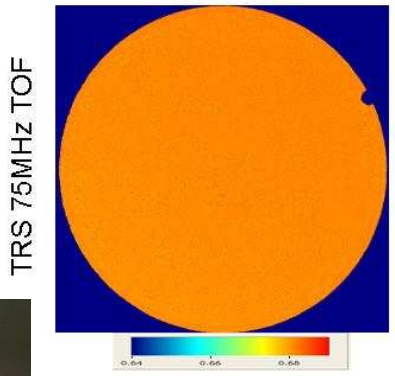
-20 dB pulse width: 0.03-0.06 us

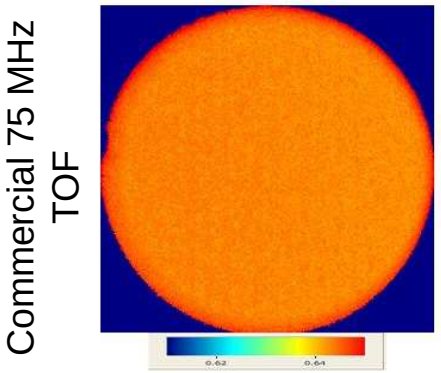
75 MHz C-Scan Experiments



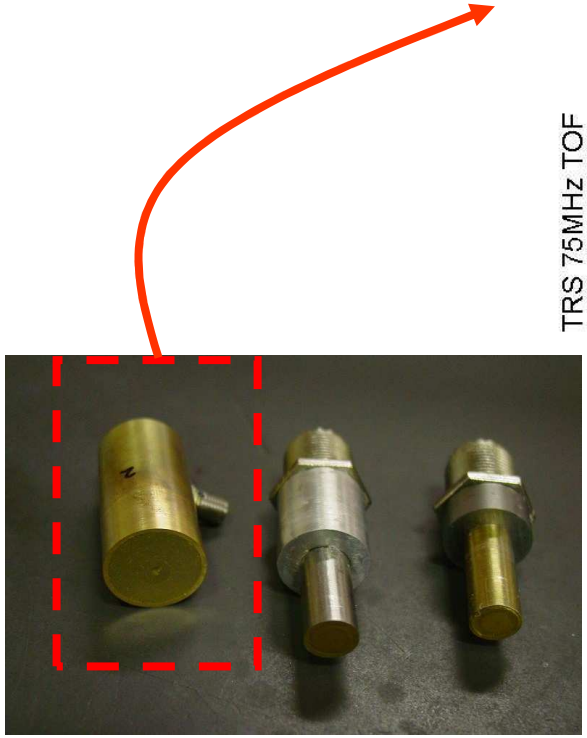


Bottom Reflected amplitude



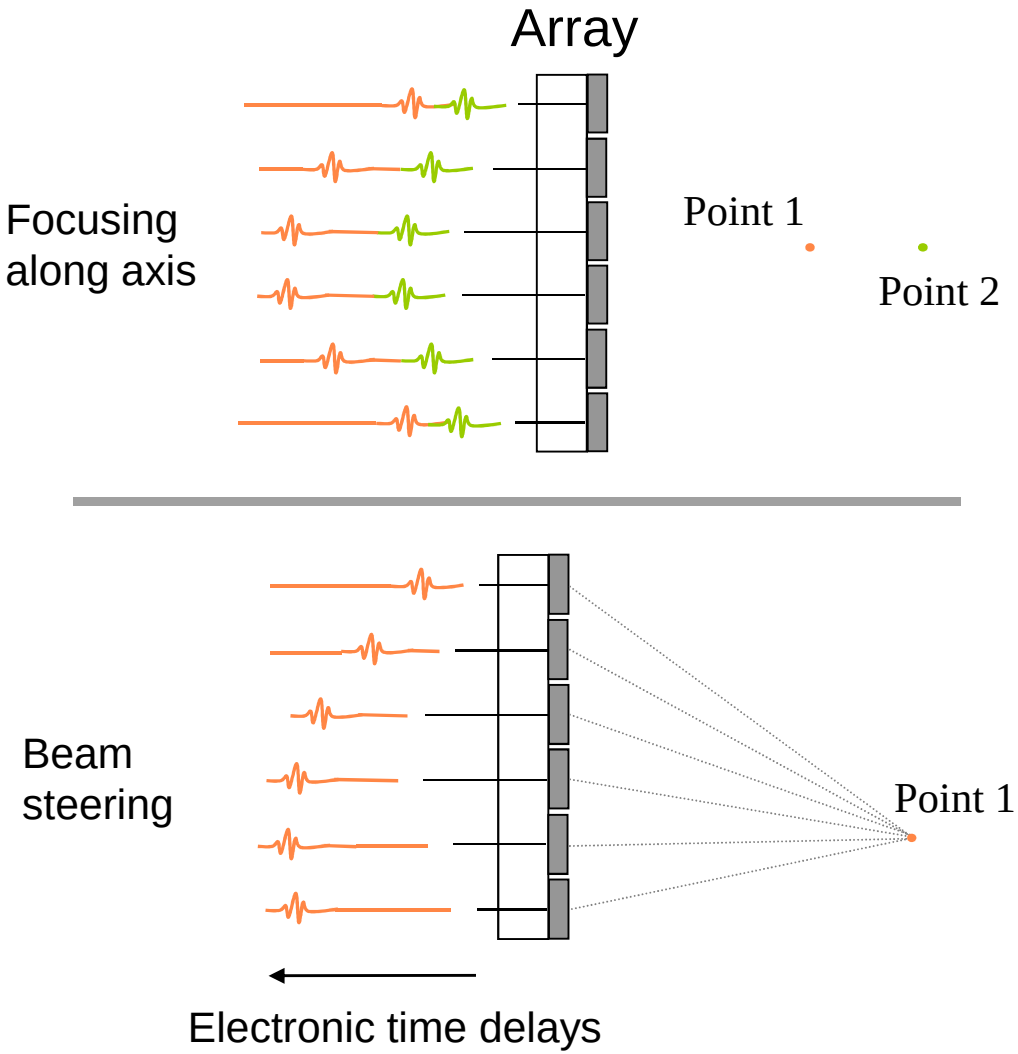


Bottom to top TOF

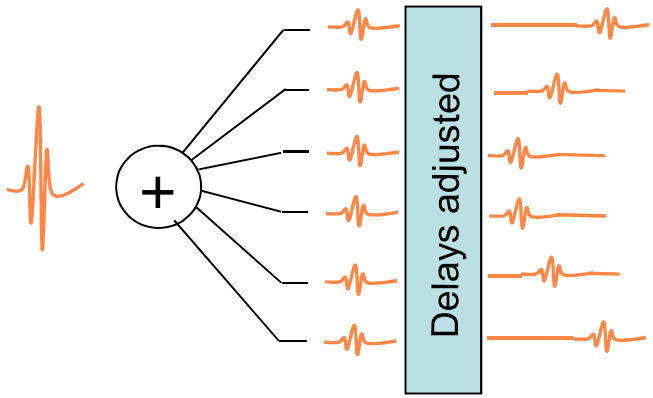


4 mm thick CVD SiC

Phased Array

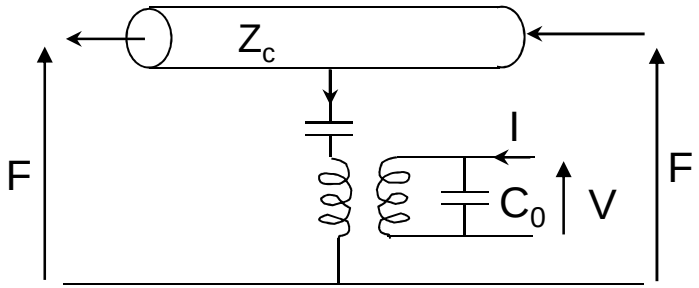


- For beamforming, use time delays so acoustic summation occurs at different points in field
- Time delays also occur in lens and physically focused transducers
- During receive, signals delayed and summed



One Dimensional Modeling

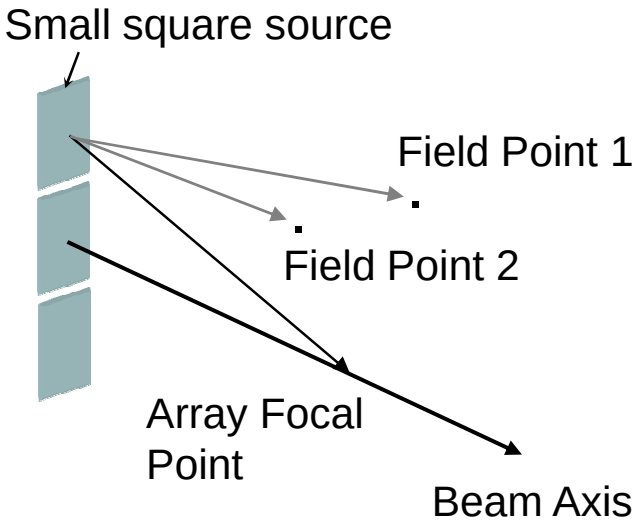
- Redwood equivalent circuit model provides representation of piezoelectric plate for compressional plane waves
- Model used to determine electroacoustic response of elements
- Incorporates transmission lines for piezo, stack layers to represent time delays, losses and reflections due to impedance mismatching
- Allows implementation of circuit components such as coaxial cables, tuning components



General Redwood circuit

Acoustic Field Modeling

- Field II* run through MATLAB
- Uses concept of spatial impulse response to calculate field
- Transducer aperture divided into small squares which allows far-field approximation to be used

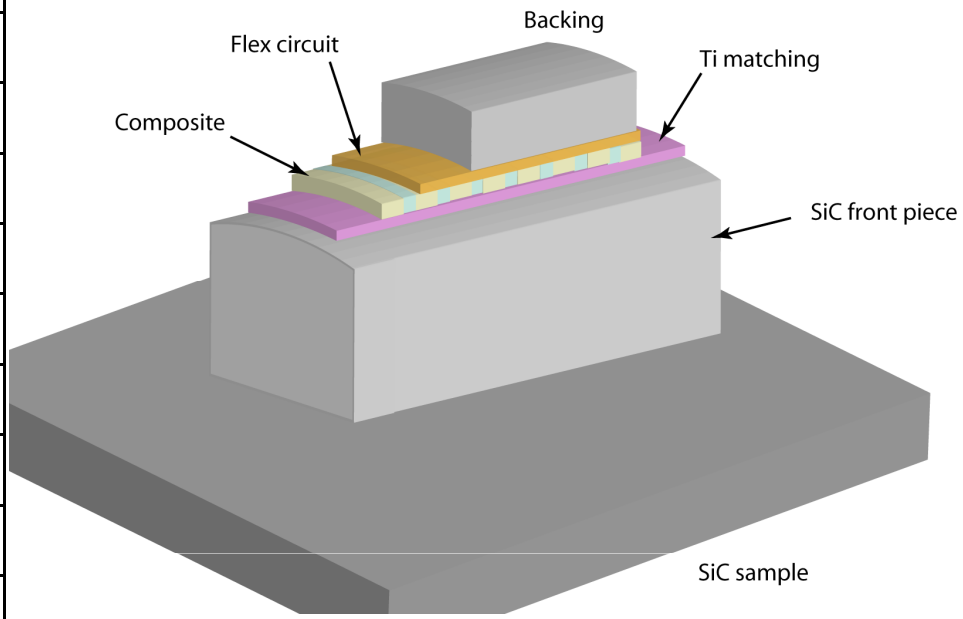


- Focusing and apodization handled through signal weighting and time delaying excitation
  - Amplitude = excitation waveform X apodization X impulse response
  - Time delay = beamformer + lens/curvature
  - All sources in one element have amplitude and time delay
- Delay and sum waveforms to achieve field waveform
- Repeat for all points in field of interest
- Attenuation linear in field, centered around attenuation at center frequency point

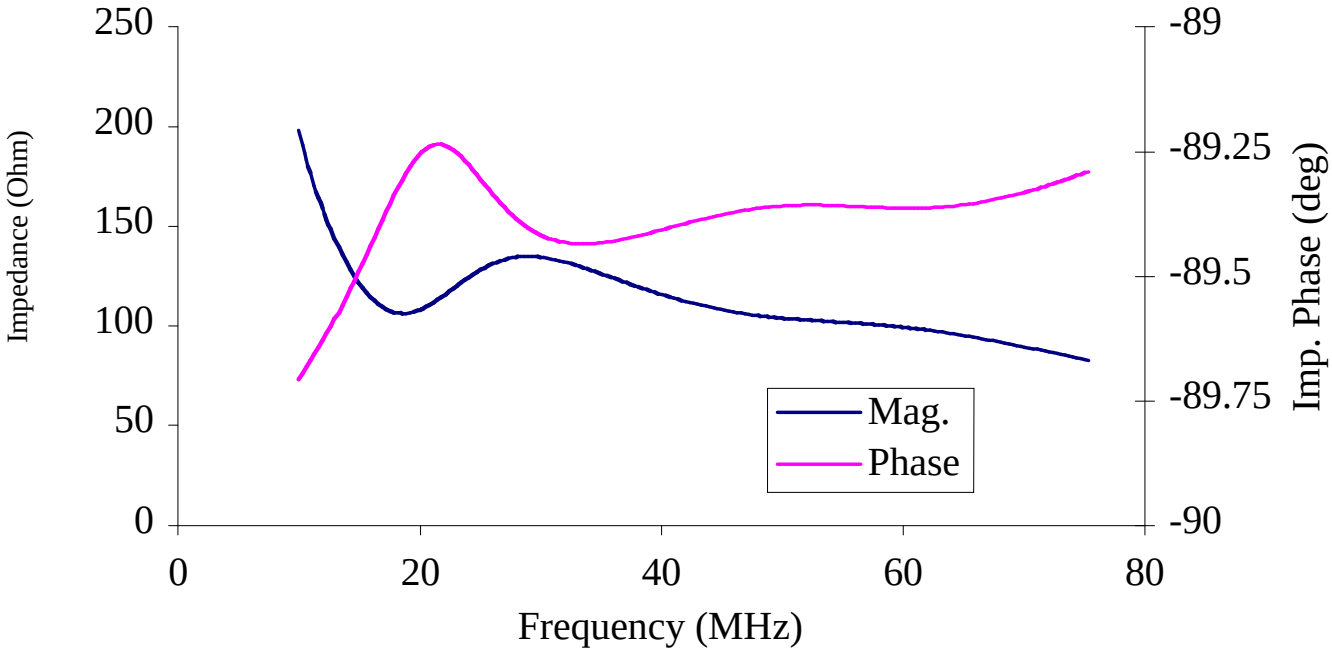
*http://www.eswww.it.dtu.dk/~jaj/field

35 MHz PCMUT Phased Array

Array center frequency	35 MHz
Elements in array	64
Array pitch	132 μm (0.4λ)
Total array azimuth	8.44 mm
PMN-PT post width	14 μm
Sub-“diced” kerf	4-5 μm
Inter-element kerf	9-10 μm
Composite thickness	35 μm
Array elevation	4 mm
Lavational focus	12 mm (f# 4.8)
Titanium matching	44 μm thick (27.3 MRayls)
Epoxy loaded backing	2-3 MRayls

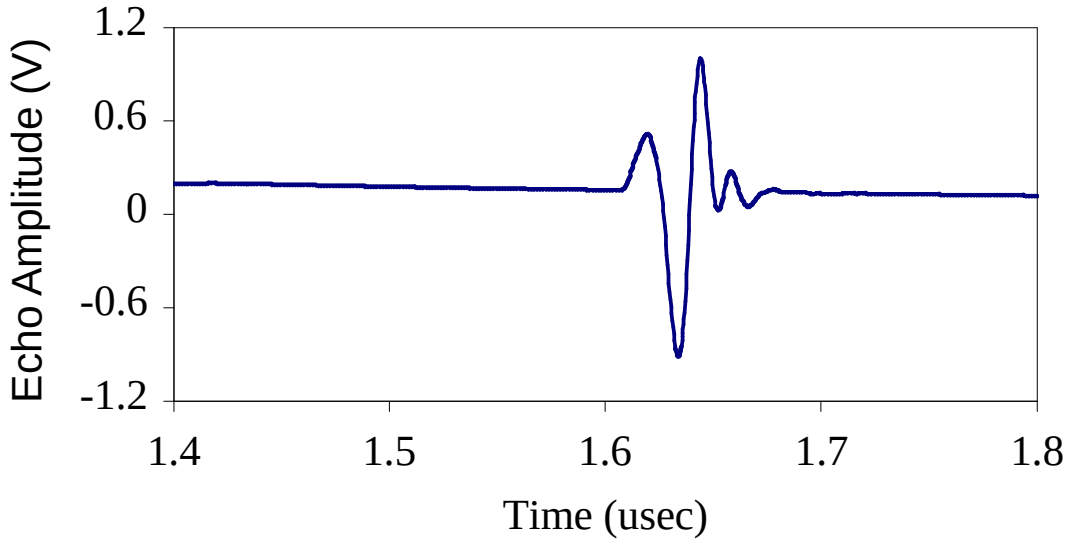


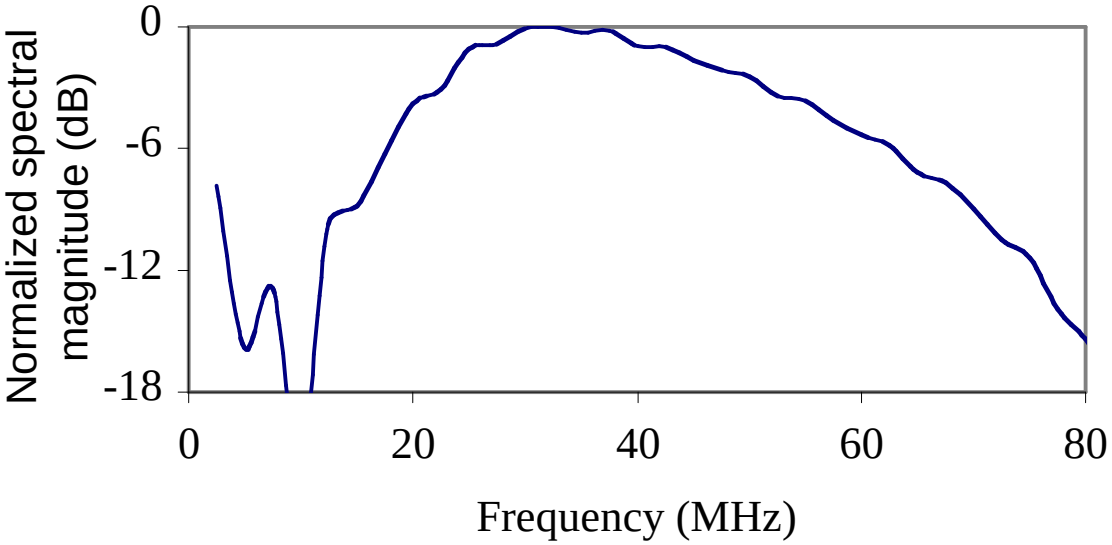
Electrical Impedance



Electrical impedance for each element ~ 150 Ohm

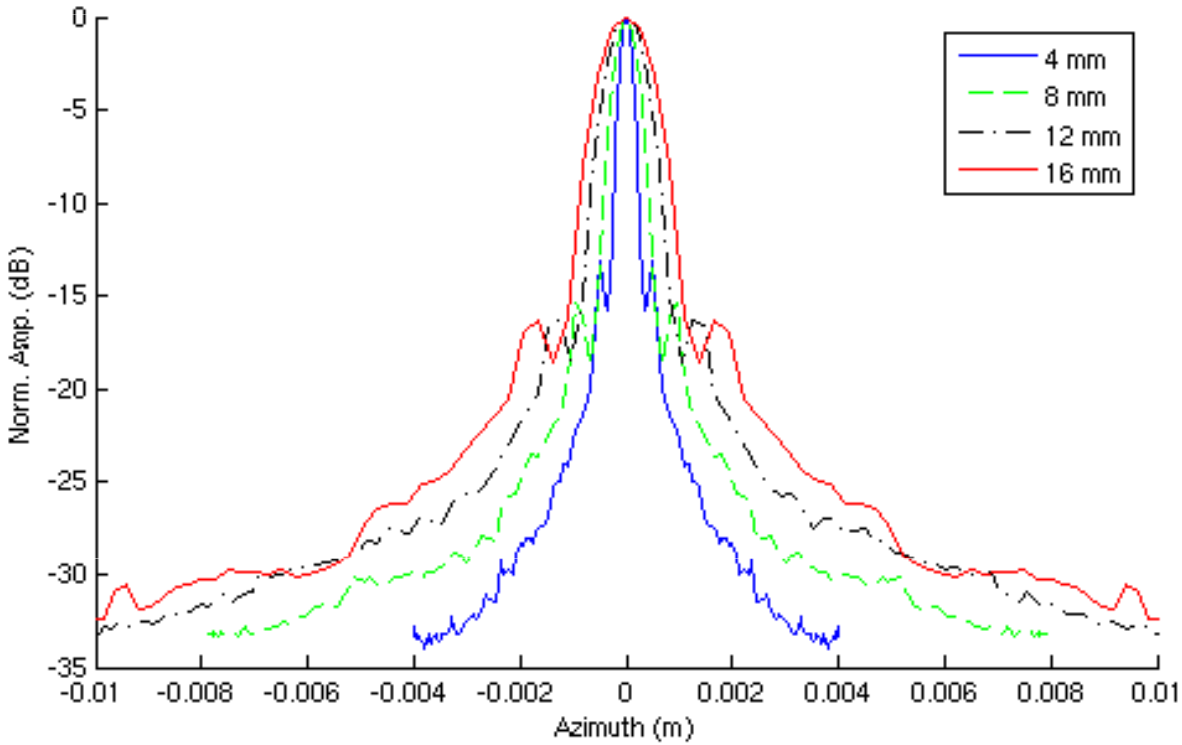
Impulse Modeling





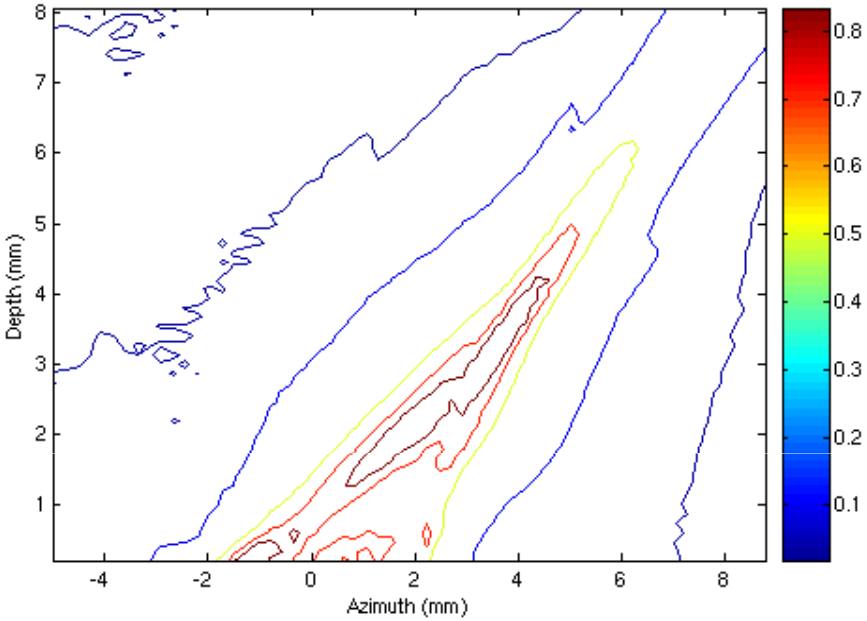
- The -20 dB ringdown of the pulse is ~ 55 ns, which corresponds to a -20 dB resolution of 633 µm (the ~ 20 ns - 6 dB ringdown corresponds to 215 µm).
- -6dB bandwidth > 80%

Acoustic Field (Focusing)

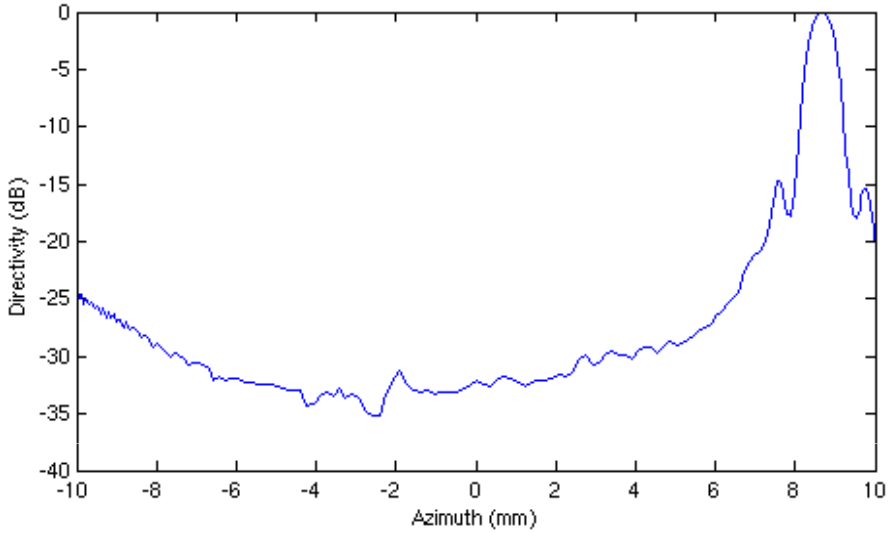


Side lobes and grating lobes are significantly lower than the main beam.

Acoustic Field: Beam Steering

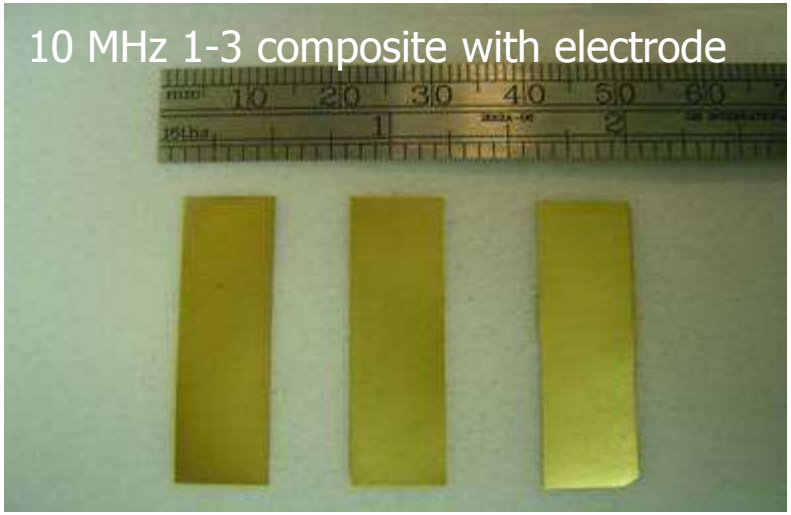


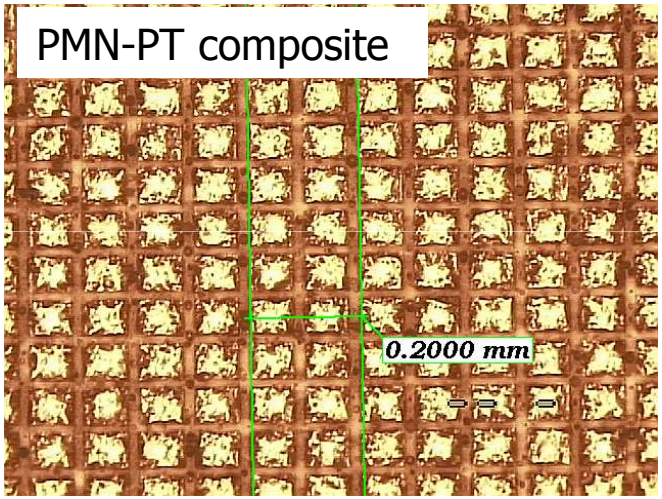
Normalized acoustic pressure plot on transmit when phased array focused to a 9 mm depth at a 45° angle

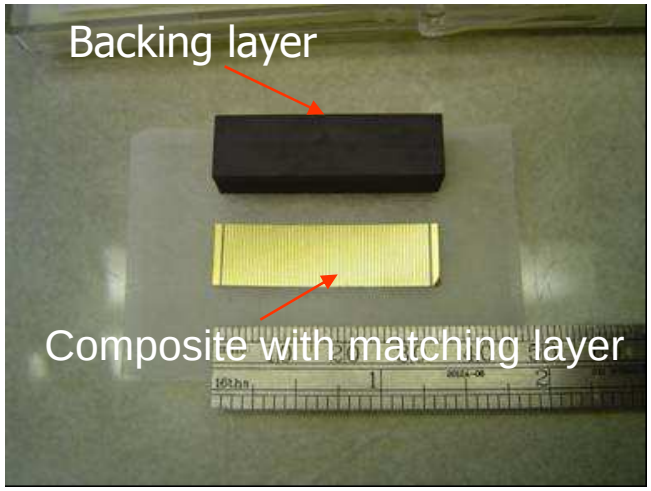


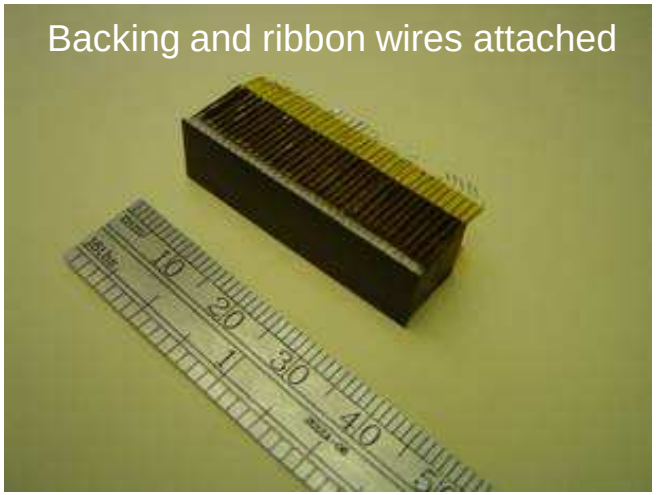
Normalized acoustic pressure at a radial distance of 10 mm (180° sweep) when focusing at 60°.

Phased Array (10 MHz) Prototyping





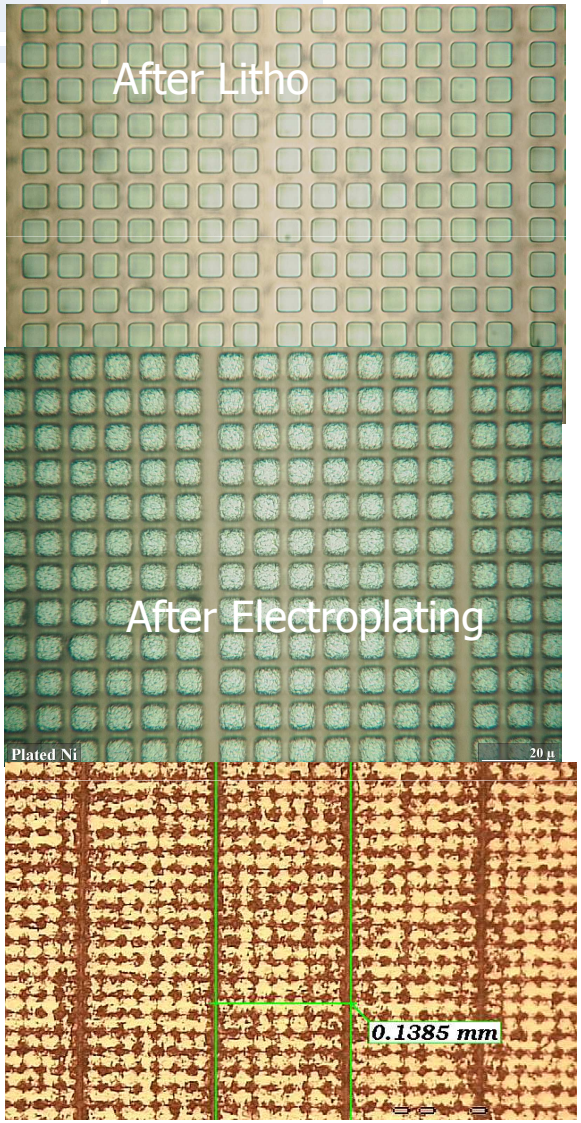




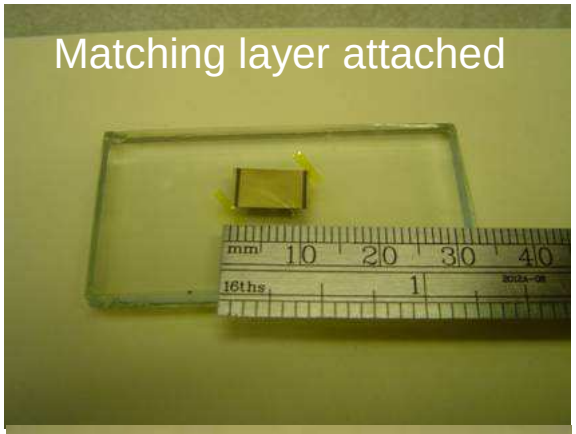
10 MHz phased array:

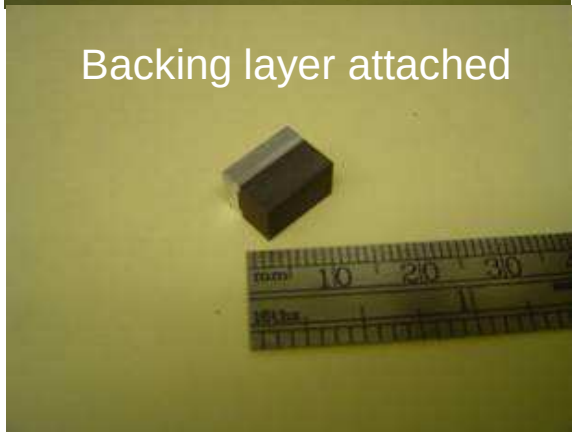
64-element; 0.5 mm pitch; 7 mm elevation

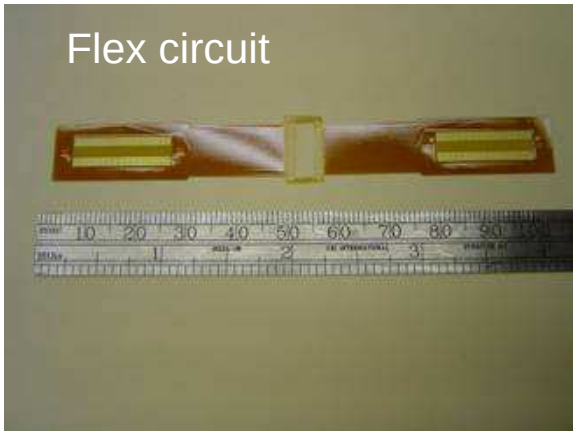
35 MHz Phased Array Prototyping

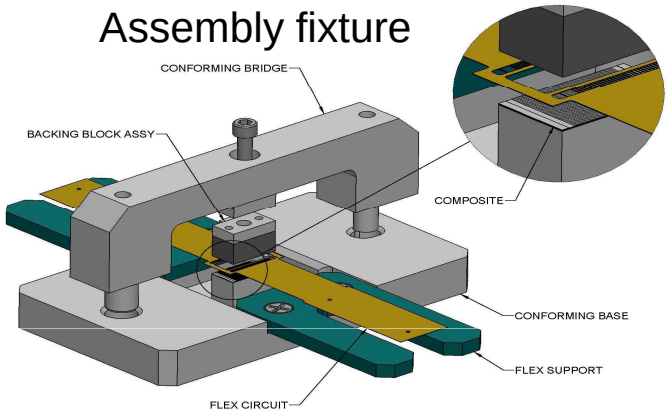


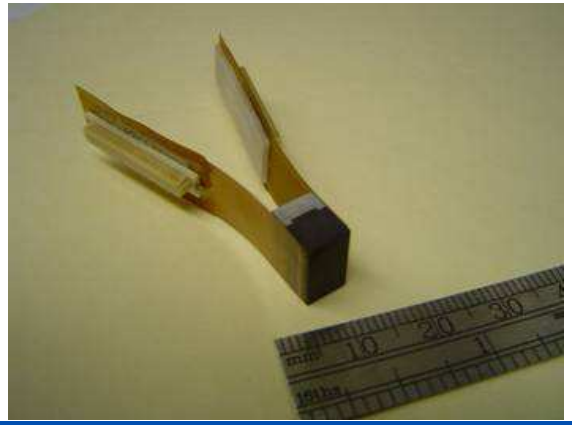
PMN-PT 1-3 composite





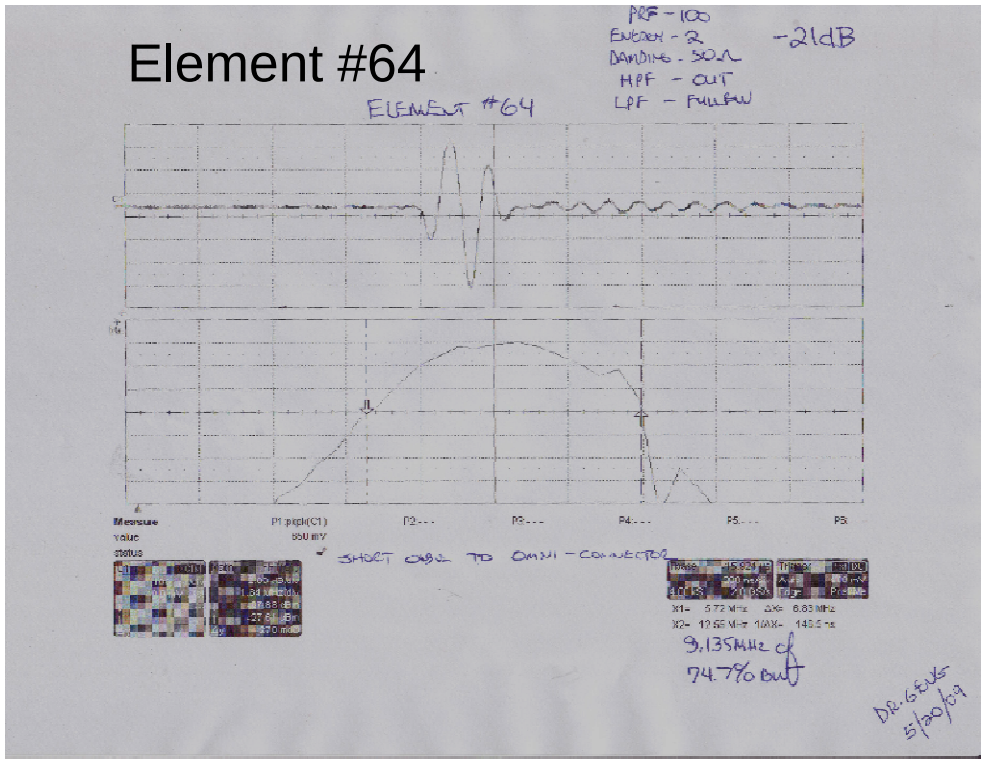


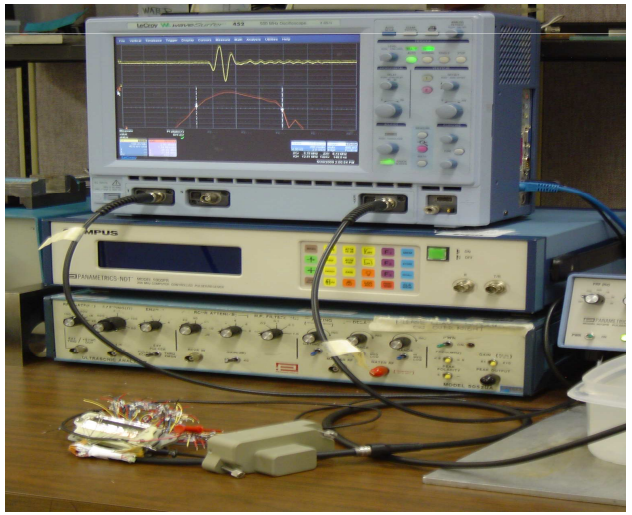


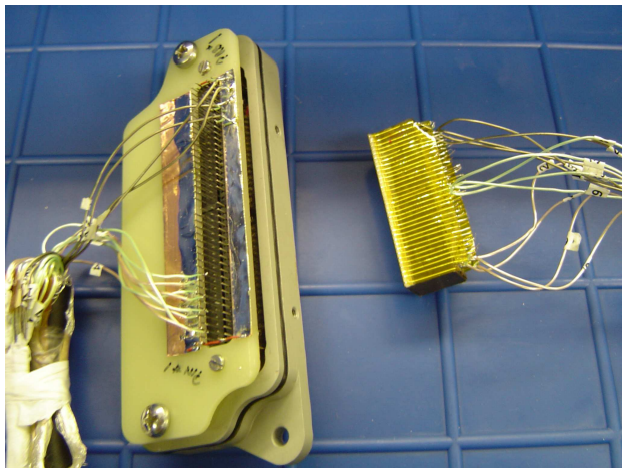


Phased Array Characterizations

Pulse-echo results for a 64-channel 10 MHz array

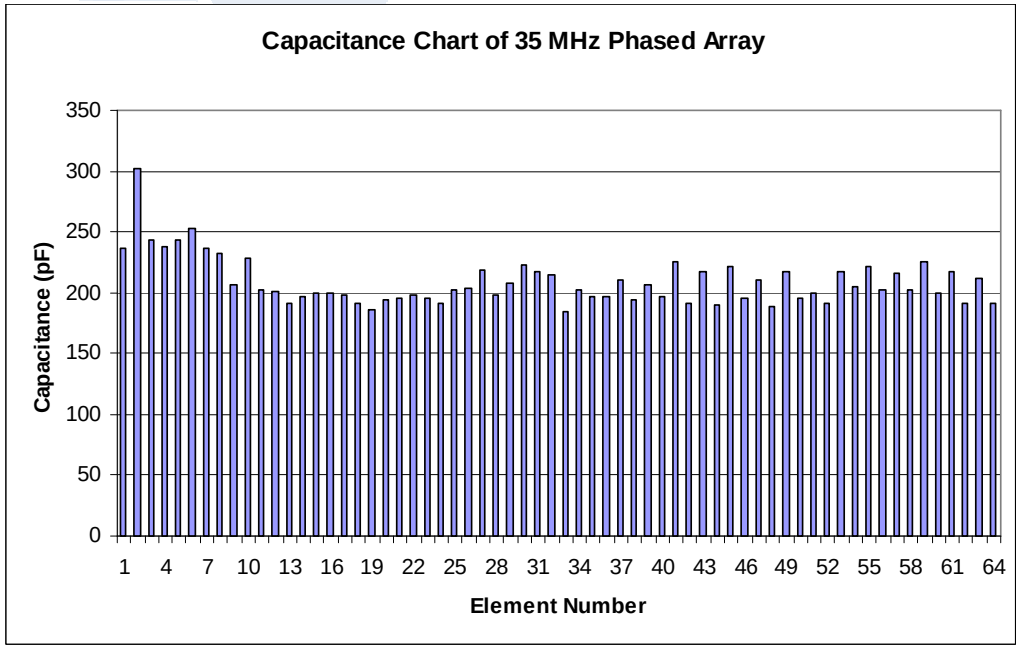


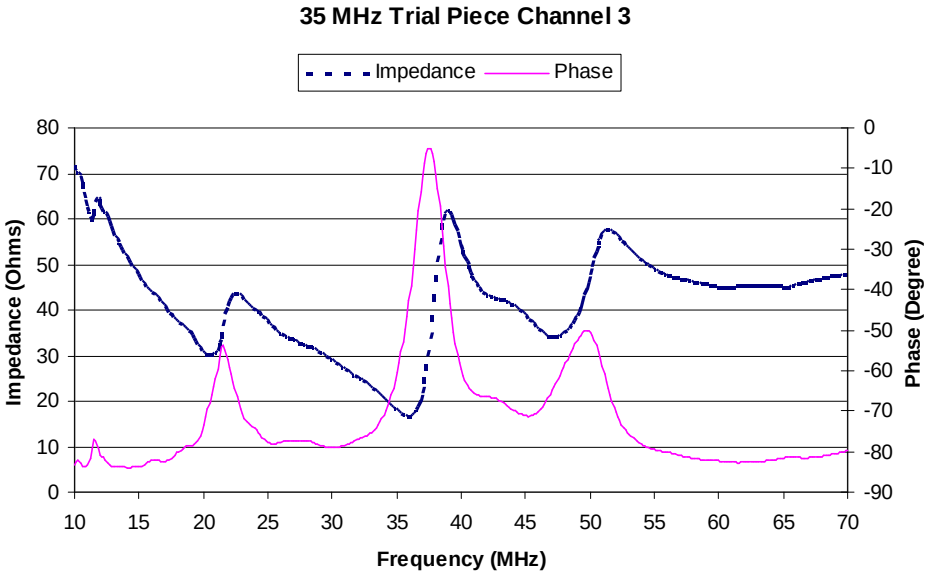




- Center frequency: 9.1 MHz
- -6dB bandwidth: ~ 75%
- Status: Cable connection and housing integration

35 MHz Phased Array Characterizations





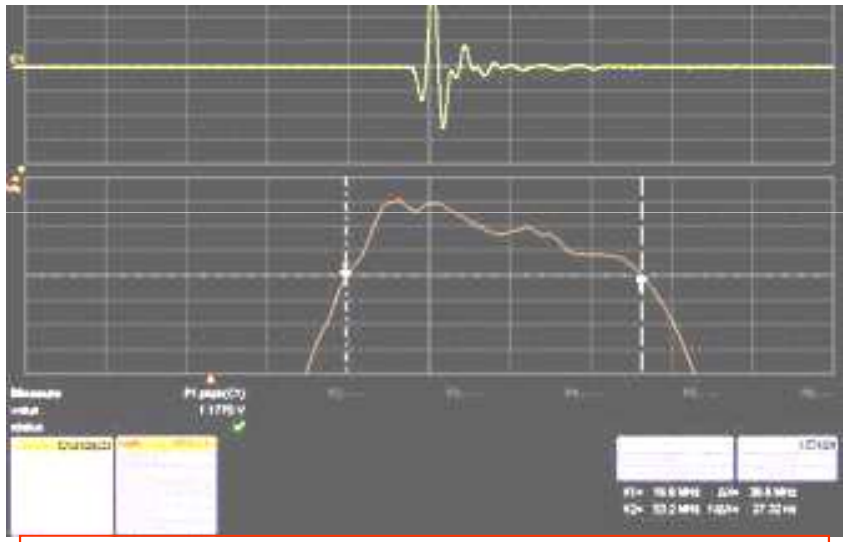
Pulse-echo Test Settings:

Panametric 5900 pulser,

1 µJ energy, net gain - attenuation =0

50 Ohms damping

LeCroy 452 500 MHz Oscilloscope



Center frequency: ~ 35 MHz

-6dB bandwidth: 80-100%

Summary and Future Work

- A 35 MHz PC-MUT phased array was designed for ceramic NDE applications.
- The -3 dB beam width on transmit varies from approximately 300 μm at 4 mm to 1.09 mm at a 16 mm depth. Considering that the detection limit is flaws that are approximately 10% of the beam width, which corresponds to 30-109 μm in the azimuth.
- The main determinations from the initial array modeling are that a sector of 90° - 120° is possible. The maximum imaging depth is more than 2 cm.
- A 64 channel 10 MHz phased array and a 64 channel 35 MHz phased array were prototyped and the initial pulse-echo tests showed promising sensitivity and bandwidth.

Future Work: NDE experiments using HF phased arrays.